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ENERGY FROM IN SITU PROCESSING OF ANTRIM OIL SHALE

Quarterly Technical Progress Report for January—March 1980

By
Lawrence J. Washington, Jr.

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April 18, 1980
Date Published

Work Performed Under Contract No. EX-76-C-01-2346

The Dow Chemical Company
Process Development Department
Midland, Michigan

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U. S. DEPARTMENT OF ENERGY

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Published April 18, 1980

Prepared for:

THE UNITED STATES
DEPARTMENT OF ENERGY
Washington, D.C. 20545

Under Contract No. DE-AC20-76LC10153

(Formerly Contract No. EX-76-C-01-2346)

OBJECTIVE AND SCOPE OF WORK

The objective of this contract is to test the technical feasibility of the in situ processing of the Antrim oil shale within the Mississippian-Devonian black shale sequence of the Michigan Basin to produce energy values. The field investigations will involve well development, fracturing, underreaming, fracture assessment, in situ ignition, and extraction of hydrocarbons. Supporting contributions will be made by subcontractors in the areas of shale characterization, environmental measurement, fracture assessment, and public policy.

ABSTRACT

Extraction trials on the new site were continued until the end of the quarter, the maximum length of time provided for in the contract. Trial F80-2, which began November 20, 1979, was terminated in February, 1980. Shale combustion was achieved during this trial and low Btu gas was recovered from production wells and from the injection well during depressurization of the formation after air injection was terminated. However, the proportion of gas recovered was low; possibly due to loss of injection gases through a break in the well casing. Trial F80-3 was carried out in March, 1980, with the burner in Well #305 which had not been previously used as an injection well. Good communication existed between Well #305 and 306 and initial recovery rates were 85-90%. Shale ignition was achieved without difficulty. Analysis of input and output gases gave a good accounting of oxygen and showed that significant quantities of shale were burning. Pressure drop between the input and output wells increased significantly during the period when there was evidence of in situ combustion. Further evaluation of this trial will be completed in the next quarter and will be included in a topical report.

SUMMARY OF PROGRESS TO DATE

This contract, which began on October 1, 1976, requires Dow to conduct shale characterization studies on Antrim shale, carry out and evaluate the results of three *in situ* fracturing experiments, carry out an *in situ* extraction trial in already existing wells, and an extraction trial in the site of the most effective fracturing experiment, and to monitor the environmental impact of these activities.

SHALE CHARACTERIZATION

A total of 11 subcontracts are in force in four Michigan universities and in the Geological Survey Division of the Michigan Department of Natural Resources. These contracts cover various aspects of resource inventory, chemical, physical and lithological characterization. Also included are projects involving the development of an *in situ* retort model and a fracturing model. Several reports have been issued, but the majority of this work will continue through fiscal 1980.

IN SITU FRACTURING AND ASSESSMENT

Hydraulic/Explosive Fracturing: During the period from May, 1977, to May, 1979, ten wells were drilled, cored and logged on the site for this experiment. Attempts to induce horizontal fractures in the initial wells, #101 and 102, were unsuccessful; vertical fractures were induced instead. Hydraulic fracturing and sand propping further enlarged these and created new vertical fractures. Four more wells were drilled near Well #102, hydrofractured and propped. Explosives were detonated in all six of the 100 series wells in late 1978, greatly improving the permeability in the region. Post-explosive tests showed that air could be injected into Well #103 at a rate of 125 scfm at 400 psig and into Well #105 at 110 scfm at 640 psig. Four more wells were completed in May, 1979, for use in additional fracture evaluation. Air permeability tests, differential temperature logging, a spinner survey and television camera logs were completed in addition to the more routine logs.

Chemical Underreaming: Five wells were drilled, cored and logged for this experiment. An acid underreaming experiment in January, 1978, with 28% hydrochloric acid produced a much smaller cavity than had been anticipated. A number of laboratory experiments with core samples were completed and a narrow region of interest was identified. In November, 1978, the central well was hydrofractured under conditions best suited to produce a horizontal fracture, but communication with the nearby wells was not achieved. Subsequently it was concluded that this site would not be used for an extraction trial and no further work was carried out on this experiment.

Explosive Underreaming: Wells #301-305 were drilled, cored and logged early in 1978. Four explosive shots were attempted in the central well, #301; three were successful. The well was cleaned after each shot and logged. The cavity was enlarged by each shot, and some casing damage occurred during the final shot. Wells #306 and 307 were drilled early in 1979 near Well #301. Coring and flow logging of these wells showed that significant fracturing had been accomplished by the shots in Well #301. In April, 1979, an explosive charge was detonated in Well #306 and in #307. Permeability and interwell communication in the 300 series were found to be comparable to that in the 100 series wells. TV logs and an airflow/tracer gas survey helped to corroborate the extent and location of the fracturing. A good communication pattern connects Wells #301, 305, 306 and, to a lesser extent, 307. For this and other reasons, the 300 series was chosen as the site for the next extraction campaign.

IN SITU EXTRACTION TRIALS

Existing Dow Site: The extraction trials planned for the existing site were completed in 1978. Two trials using an electric heater to initiate combustion were aborted after electrical short circuits occurred. After the heater was modified, it operated for several days and analysis of effluent gases indicated that combustion had been sustained for up to ten days.

A coal and charcoal augmented combustion trial was conducted in Well #4 in February, 1978, using a propane burner for ignition. Combustion was maintained at a high level for about one week, and CO_2 and CO were present in the effluent gases for another ten days. Greater quantities of hydrocarbons, carbon monoxide and hydrogen were produced than during previous trials.

A charcoal augmented combustion trial in Well #7 began at the end of March, 1978, and continued for 61 days, while several continuous and cyclic production procedures were tested. Gas having energy values in the target range (150 Btu/scf) was produced at various times, although the flow rate at these times was minimal and hence the energy production was low. There was no significant heat damage to the propane burner, whereas in the previous run the burner was severely damaged. Analysis of product gases showed a total energy content 4.9 times that of the total solid and gaseous fuel put into the well for ignition.

In March, 1979, in preparation for the extraction trial to be run on the new site, a downhole methane burner developed by Tejas Petroleum Engineers, Inc. and operated by TOR Development, Inc., was tested in an existing well under realistic operating conditions. The burner operated successfully for more than 80 hours and was reignited several times without difficulty. This burner was modified for use in subsequent extraction trials.

New Dow Site: Using redesigned equipment and modified operating procedures, based on knowledge gained by the experiences in the extraction trials on the existing site, preparations for a new series of extraction trials were completed during the last quarter of FY'79. Extraction trial F80-1 was initiated in October, 1979, using an ignition service provided by TOR Developments, Inc. A methane burner was installed in Well #301 which was then equipped with the necessary auxiliary piping and the explosion protection barrier. Burner ignition was readily obtained and shale combustion occurred within two days. Combustion in the wellbore was so intense that the burner was lost and shale combustion decreased thereafter. Therefore, the trial was terminated.

After modification to permit better air cooling, extraction trial F80-2 was begun late in November, 1979. During this trial, which continued until mid-February, combustion was maintained with intermittent use of injected methane. However, recovery of injected gases during much of the run was quite low; near the end recovery was down to about 6%. During depressurization after air injection had been stopped, significant amounts of low Btu gas was recovered and it became apparent that much of the injected gas may have been lost through a break in the casing.

The final trial, F80-3, was carried out in March, 1980, using a fresh well for injection. Combustion was achieved readily and good material balances of injected oxygen were obtained. Again the limited quantities of low Btu gas were produced and resistance to flow through the formation increased significantly when the formation was hot.

ENVIRONMENTAL, PUBLIC POLICY AND LEGAL ASSESSMENT

Environmental Monitoring: A subcontract with the Environmental Research Institute of Michigan (ERIM) requires ERIM to monitor land, air and water quality impacts of experimental activities at the Sanilac County site. The only major environmental impact has been the surface disturbance to the site due to the well drilling and completion activities and the fracturing and assessment activities. No air or water quality problems due to activities during this contract have been observed. This work was stopped midway of the first quarter of FY'80 due to the delay in the release of FY'80 funds and resumed in mid-March, 1980.

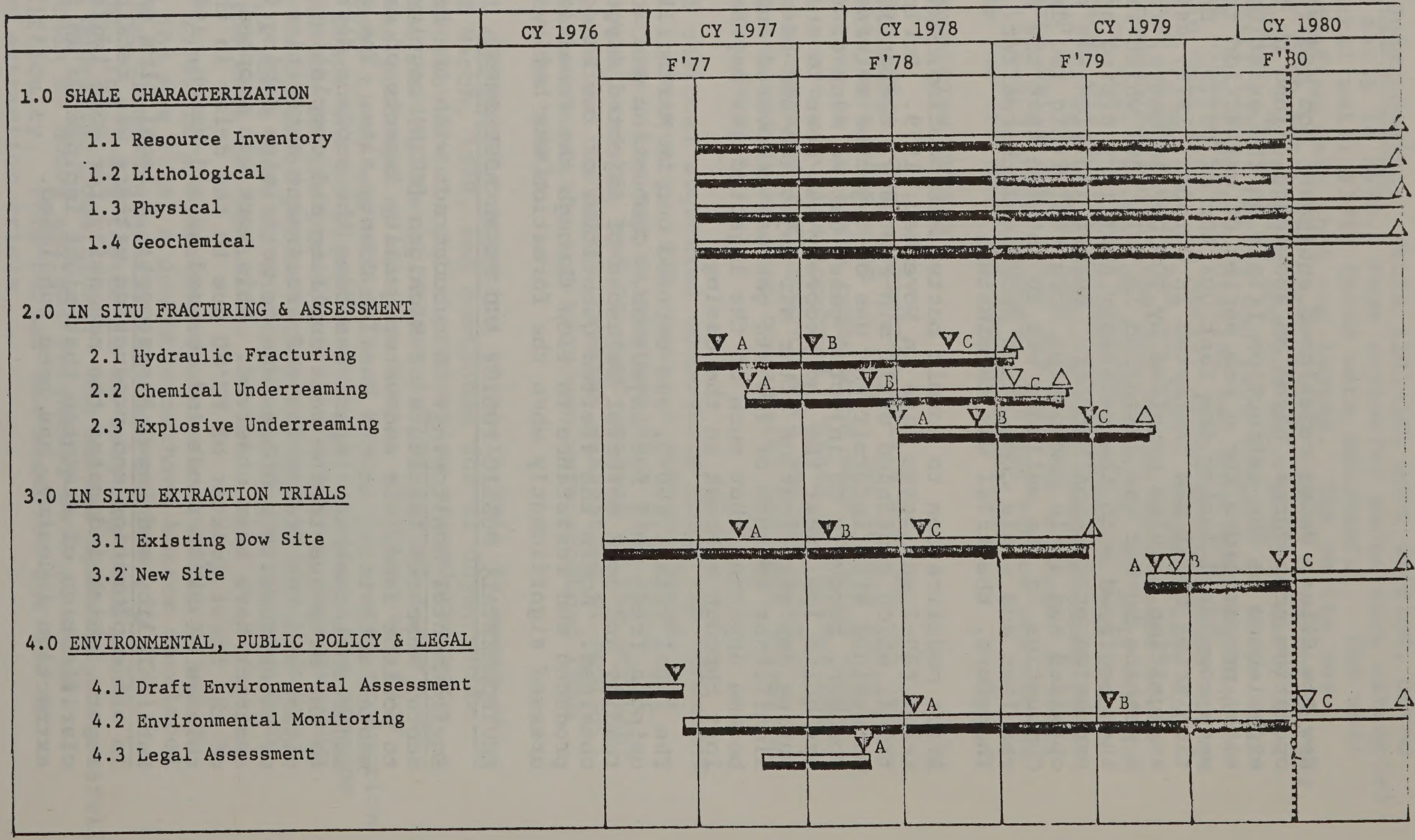
Public Policy and Legal Assessment: A legal firm experienced in oil exploration and production matters was retained. Their report, which indicates the necessity for some legislative clarification of statutes that might impinge on an in situ extraction industry, has been published.

Legend

Planned: ▭
Actual: ▬
Intermediate Event: ▽
Completed: ▼
Milestone: △

MILESTONE CHART
CONTRACT NUMBER: DE-AC20-76LC10153*
ENERGY FROM IN SITU PROCESSING OF ANTRIM SHALE
Project Manager: L. J. Washington, Jr.

Date: April 18, 1980
Report No: FE-2346-64



*Formerly Contract No. EX-76-C-01-2346

CONTRACT DE-AC20-76LC10153

(formerly contract #EX-76-C-01-2346)

MILESTONE CHART

(Showing Intermediate Events and Milestone Points)

Task	Event or Milestone Point	Date
1.0	Δ Summary report - all subtasks	9/80
2.1A	∇ Drill and core wells #101 and #102	6/77
B	∇ Initial hydraulic fracturing	10/77
C	∇ Explosive fracturing	7/78
	Δ Assess results	10/78
2.2A	∇ Drill and core well #201	7/77
B	∇ Initial acid underreaming	2/78
C	∇ Explosive fracturing	11/78
	Δ Assess results	2/79
2.3A	∇ Drill and core well #301	3/78
B	∇ Initial explosive underream	8/78
C	∇ Explosive fracturing	4/79
	Δ Assess results	6/79
3.1A	∇ Initial permeability study	7/77
B	∇ Three-week combustion trial	12/77
C	∇ Complete combustion tests	6/78
	Δ Complete site observation and abandon location	4/79
3.2A	∇ Identify second site for combustion tests	7/79
B	∇ Begin combustion tests	8/79
C	∇ Complete combustion tests	2/80
	Δ Complete site observation	9/80
4.1	Δ Draft environmental assessment accepted	1/77
4.2A	∇ Update environmental assessment	4/78
B	∇ Update environmental assessment	4/79
C	∇ Update environmental assessment	4/80
	Δ Summary assessment	9/80
4.3A	∇ Complete initial legal assessment	2/78

SHALE CHARACTERIZATION

RESOURCE INVENTORY

The collection and organization of information which will be used for the preparation of stratigraphic maps is continuing at Michigan State University (MSU) under the direction of Dr. Fisher. A list of the tops of the Traverse Formation, the drafting of cross-sections, data charts and three gamma ray cross-sections of the wells which have been sampled for this project were all completed. These items will be used by other subcontractors in compiling their shale characterization data. The series of maps of the bedrock in the Michigan Basin is now ready for drafting.

Under the direction of Dr. Cross at MSU, work on samples from four wells across the center of the state continues. He reports that all of the samples contain palynomorphs. There is vertical fluctuation in both abundance and diversity of these palynomorphs in each of the sample sequences under investigation. They are continuing the process of identifying the palynomorphs while counting (spores per gram of sample) into informal spore-type groups to evaluate these fluctuations.

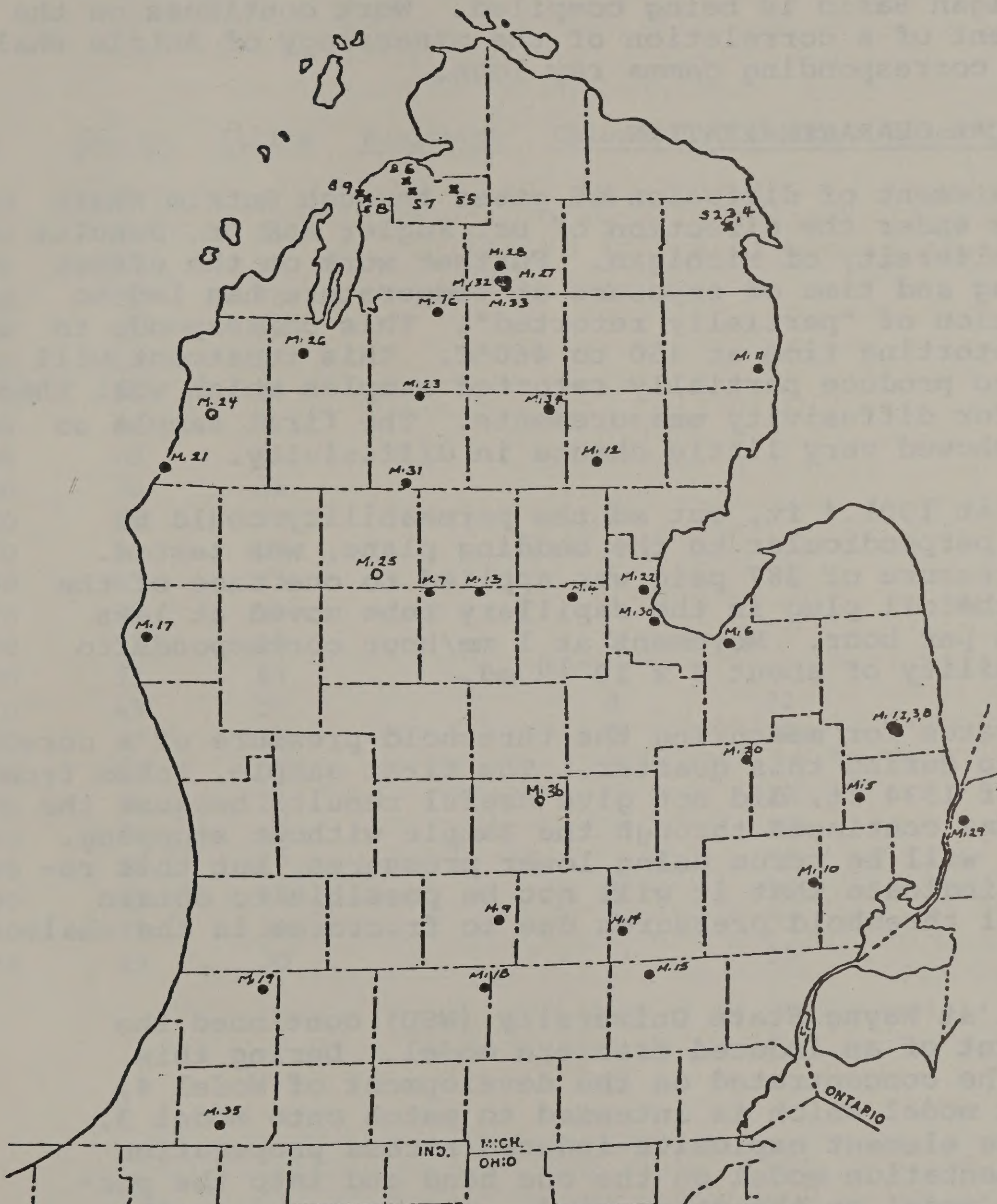
The state of spore preservation does vary among the samples. The source of this variation can probably be found both in the processing techniques, which have been evolving throughout the project, and indigenous sample variation. The processing sequence that was effective for the majority of the first samples macerated produced less than satisfactory results from a number of the later samples. Subsequently, a maceration sequence has been found that seems to produce good quality residues, and uniformly so.

Counting of samples from three wells has begun. In general, the lower Bedford (Ellsworth?) and upper Antrim microfossils are in quite good condition in two of the wells. They are quite poorly preserved in the other samples, although an occasional identifiable spore may be seen. At least eight identifiable genera of trilete spores have been seen during counting thus far.

Samples from three more wells have been sent to the subcontractors for shale characterization studies. The locations of all wells which have been sent for processing are shown in Figure 80-Q2-1.

FIGURE 80-Q2-1

SAMPLES TAKEN IN THE MICHIGAN BASIN FOR RESOURCE INVENTORY OR SHALE CHARACTERIZATION



● Wells Sampled Previously

○ Wells Sampled This Quarter

X Outcrop Samples

LITHOLOGICAL CHARACTERIZATION

Dr. Routsala of Michigan Technological University (MTU) has completed the semi-quantitative X-ray mineralogical analysis of 174 samples from Wells Mi-23, 25, 26, 34, 35 and 36. The data from one of these wells is compiled in Table 80-Q2-1. The information needed to complete three cross-sections of the Michigan Basin is being compiled. Work continues on the development of a correlation of the mineralogy of Antrim shale with the corresponding gamma ray logs.

GEOPHYSICAL CHARACTERIZATION

The measurement of diffusion of gases through Antrim shale continues under the direction of Dr. Fogler and Dr. Schultz at the University of Michigan. Further work on the effect of heating and time of exposure at temperature has led to a definition of "partially retorted". This corresponds to a long retorting time at 450 to 460°C. This treatment will be used to produce partially retorted samples which will then be used for diffusivity measurements. The first sample so treated showed very little change in diffusivity.

A sample at 1301.4 ft, cut so the permeability could be measured perpendicular to the bedding plane, was tested. When a pressure of 387 psig was applied to one face of the sample, the oil plug in the capillary tube moved at less than 1 mm per hour. Movement at 1 mm/hour corresponds to a permeability of about 3×10^{-10} md.

The apparatus for measuring the threshold pressure of a core was set up during this quarter. The first sample, taken from a depth of 1334 ft, did not give useful results because the flow of gas continued through the sample without stopping. The trial will be rerun using lower pressures, but this result may indicate that it will not be possible to obtain meaningful threshold pressures due to fractures in the shale.

Dr. Carmi at Wayne State University (WSU) continued the development of an induced fracture model. During this quarter, he concentrated on the development of Model 4, the crack model which is intended to match onto Model 3, the finite element explosive-induced stress propagation and fragmentation model on the one hand and into the permeability model on the other hand. The next phase will involve the definition of the coalescence and fragmentation parameters which will quantify the amount of rock fracturing and thus help determine permeability.

TABLE 80-Q2-1

MINERAL CONTENT OF SAMPLES FROM WELL MI-23

Depth	Quartz	Illite	Kaolinite	Chlorite	Calcite	Dolomite	Pyrite
2500-10	27	27		9		43	
10-20	33	26		2		39	
20-30	35	20		3		42	
30-40	65	31		4			
40-50	67	33					
50-60	63	27					10
60-70	76	24					
70-80	71	24					5
80-90	70	25					5
90-00	70	25					5
2600-10	58	39		3			
10-20	63	33					4
20-30	63	33		4			
30-40	39	28		3		30	
40-50	53	40		3			4
50-60	57	43					
60-70	43	32		3	22		
70-80	47	30		3	20		
80-90	60	37		3			
90-00	54	23			23		
2700-10	44	19			37		
10-20	32	17			51		
20-30	45	24		5	26		
30-40	29	16		2	53		
40-50	25	20			55		

GEOCHEMICAL CHARACTERIZATION

Geochemical analysis work continued at MTU under the direction of Dr. Leddy.

CHN analysis has been completed on Wells Mi-34 and Mi-35. With the exception of two samples near the bottom of the Antrim which contained over 11% carbon, the samples from Well Mi-34 showed a range of 2-8% C. Analyses for boron, bromine, chlorine, fluorine, and phosphorus have been completed on Wells Mi-1 through Mi-3. The results are summarized below. Boron and chlorine analyses have been done on several other wells, but due to the time consuming nature of the procedures, no further wet analyses are planned. Most of the analyses that have been done by atomic absorption or wet analysis in the past are now being done by X-ray fluorescence.

	Well Mi-1	Well Mi-2	Well Mi-3
Br, %	0.2 - 0.9	0.2 - 1.5	0.2 - 0.9
Cl, %	0.4 - 2.1	0.2 - 1.8	0.4 - 1.7
P, ppm	60 - 610	110 - 1070	80 - 610
B, ppm	300 - 2300	100 - 2300	110 - 3200
F, ppm	320 - 1440	20 - 100	70 - 110

Organic characterization of oil shale at MTU is under the direction of Dr. Sandel. Bitumen extraction of the samples from Well Mi-25 were completed this quarter. This core showed the second highest bitumen content found to date, 0.2-0.9%. The samples near the center of the Michigan Basin, those with the greatest depth, have higher bitumen content. The wells showing the greatest bitumen content are Wells Mi-7, 25, 4, and 13.

Low temperature ashing of all samples from Wells Mi-26, 34 and 35 has been completed. Only two samples (Well Mi-34, 2090-3000, 12.5% and 3000-3010, 11.2%) had more than 10% organic material. The other samples were in the range of 1-8%.

An alkaline permanganate oxidation of kerogen concentrates from Well Mi-1, 1410.6-1411, has been previously reported. The 22 samples of organic acids obtained from this oxidation were separated into two groups of 11, water soluble and water insoluble. During the past quarter, extensive capillary gas chromatographic work has been carried out on these samples in preparation for capillary gas chromatography-mass spectrometric analysis (GC-MS). Standardized conditions were sought which would allow good separation within each group of 11 samples so that compounds identified by MS in one sample could be identified by retention times in similar samples. This would minimize the need for much more expensive GC-MS analyses. The goal was met for the water soluble acid esters and three of the samples chosen for GC-MS analysis are presently being analyzed. GC work with the water insoluble acid esters has been far less successful. Very little material goes through the capillary columns. These samples are undoubtedly comprised largely of substances with molecular weights too high to pass through capillary columns. A six foot Dexsil 300 column with a high temperature limit of 450°C has been purchased to be used with these samples.

Large scale bitumen extraction work at MTU is under the direction of Dr. G. Swartz. Column chromatography on Mi-3, 1318-1328 is now complete. The hydrocarbon fraction from the previous alumina column has been chromatographed on silica gel. Glass capillary gas chromatography on the Mi-3 samples 1318-1328 ft and 1328-1338 ft is underway. GC parameters optimized for Paxton Quarry paraffin concentrate (i.e. hexane eluent from column chromatography on silica gel) have been used for similar fractionation of Mi-3. By comparison with standards the homologous series of straight chain hydrocarbons is likely to be present in all three samples. The estimate of carbon number is approximately C_{12} and to C_{30}. While the majority of the peaks in the three samples have good matches by relative retention time, their concentrations vary among the three samples, Paxton Quarry and the two Mi-3 composites. Accurate assessment awaits quantitation of the data. Preliminary spectroscopic data indicate little difference between Paxton Quarry and the Mi-3 core samples.

Fischer Retort Assays on samples from Mi-26, 34 and 35 were completed by the group under Dr. Leffert and Dr. Schroeder (WSU). Calculations on the 56 samples from Mi-34 have not been completed. Oil yields from Mi-26 were in the range 1.5-10 gal/ton; from Mi-35 they were 5-9 gal/ton.

IN SITU EXTRACTION

EXTRACTION TRIAL F80-2

Review of Extraction Period, Nov. 27 - Dec. 31, 1979

Details for the first half of the extraction phase of trial F80-2 are given in the last quarterly progress report, #FE-2346-58. This period of operation can be typified by the following statements:

11/27-12/10/79	Burner used to heat cavity. Temperature steadily increased until shale ignited.
12/11-12/12/79	Excellent shale combustion.
12/13-12/27/79	Shale combustion continued but much of the combustion O_2 was not consumed, leaving 5-12% O_2 in the production gas. Recovery dropped to 6%.
12/27-12/31/79	Good shale combustion. Methane burning in the formation rather than at the burner. Production gas had 1% O_2 content to 12/31. Recovery still low.

January 1 to January 11

Combustion continued at a good level. See Figure 80-Q2-2. The supplemental methane injection was stopped on January 3, and production data from Well #305 remained relatively unchanged for five days. The oxygen content rose slightly from 1.6% to 2.4% in Well #305. Well #306 showed a different array of data, especially in that, although the amount of CO_2 present was relatively unchanged, the oxygen content began increasing immediately and reached 8.5% O_2 on January 5. This indicated that less of the oxygen entering the cracks to Well #306 was being consumed. The casing air flow was stopped from January 8-11 and the burner air flow was increased by an equivalent amount, 20 scfm. By January 11, the production gas contained 12% O_2. The production gas flow had increased to give over 20% recovery, probably because formation cooling had allowed the cracks to open wide. There was apparently good transmission of the injected downhole air to the production wells.

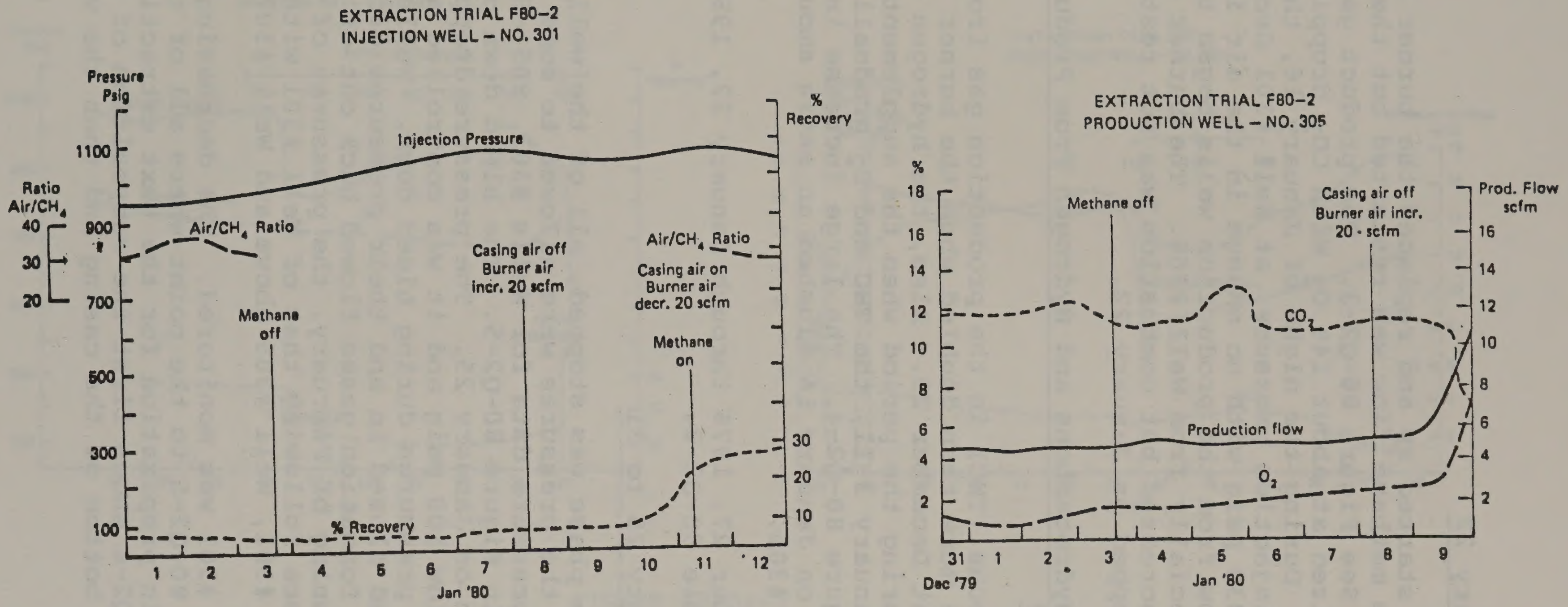


FIGURE 80-Q2-2

DATA FROM INJECTION AND PRODUCTION WELLS, EARLY JANUARY

January 11 to January 22

The casing air was started up and replaced the burner air on January 11. The methane flow was restarted but the fire did not start up. See Figure 80-Q2-3. The product gas composition stabilized at about 14% O_2 with CO_2 dropping from 4.5% to 3.5%. During the night of January 16, the back pressure, or injection pressure, at Well #301 dropped from 1050 psig to 830 psig with no change in the air injection rate. The flow from the production wells began to also decrease, especially from Well #306. The burner air and methane were increased but combustion was not restored and the run was stopped on January 22.

Analyses of Total Hydrocarbons and Hydrogen From Production Wells, January 1-22

The total hydrocarbons (THC) in the production gas from Wells #305 and #306 more than doubled when the burner flame went out about December 25. Also, the hydrogen content increased. During the period when the supplemental methane was off, January 3-11, the THC and H_2 gradually decreased. See Figure 80-Q2-4. The large increase in injection air flow on January 16 flushed an extra amount of THC out of Well #306.

The data for December 27, 1979 through January 22, 1980 are compared in Table 80-Q2-2.

Bleed Period, January 25 to 31

When the extraction phase was stopped, all of the wells were closed in and the pressures were allowed to come to equilibrium. The pressure data for Wells #301, 305, 306 and 307 are shown in Figure 80-Q2-5. The bleed down of Well #301 was begun on January 25. The pressure dropped very rapidly to below 100 psig and it was controlled at successively lower pressures during bleed down. Wells #305, 306 and 307 remained closed in and their pressures dropped more slowly as the formation gases flowed back out of Well #301. By the beginning of February, the pressures of the production wells were following that of Well #301 with Well #306 close to #301, Well #305 above and Well #307 below.

The flow from Well #301 was monitored. The decreasing rate is shown in Figure 80-Q2-5 to the point where all of the wells were opened in preparation for the next extraction trial. Figure 80-Q2-6 shows first the composition of the gases entering the bottom of the casing and then the vent

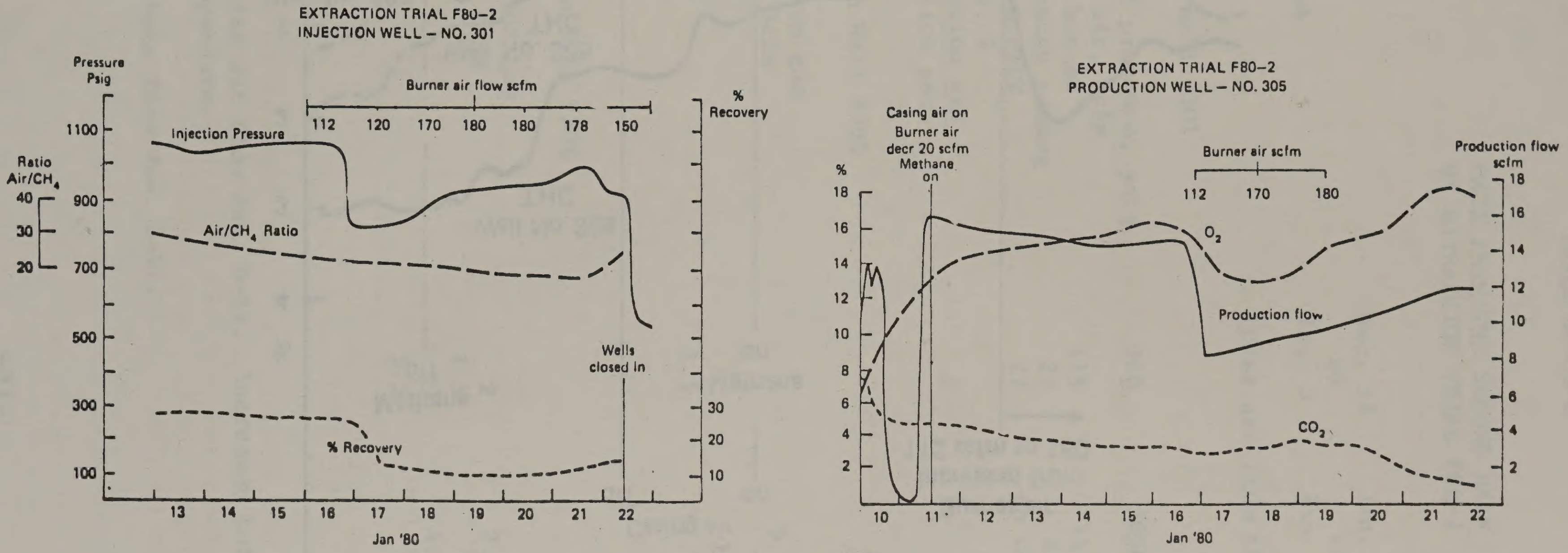


FIGURE 80-Q2-3

DATA FROM INJECTION AND PRODUCTION WELLS, MID-JANUARY

FIGURE 80-Q2-4

EXTRACTION TRIAL F80–2
ANALYSES OF TOTAL HYDROCARBONS AND HYDROGEN
FROM PRODUCTION WELLS

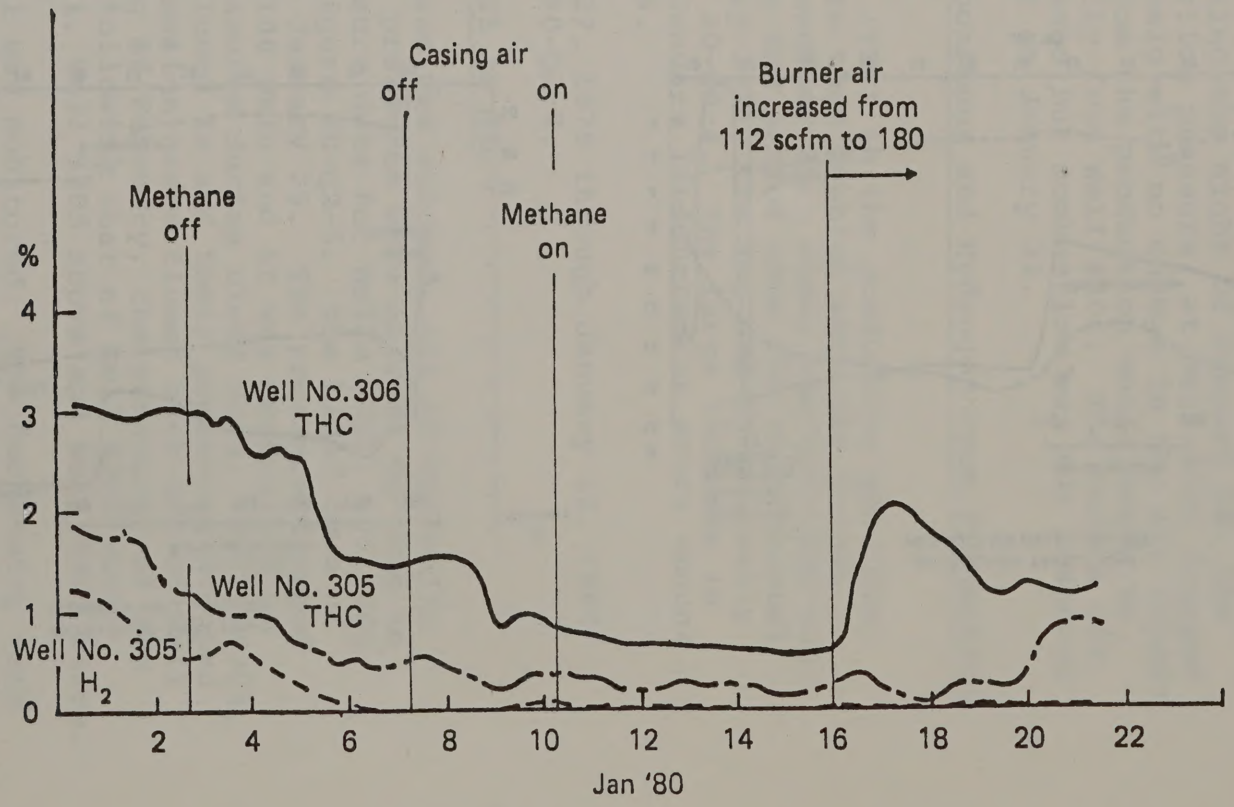


TABLE 80-Q2-2

DATA FROM THE SECOND HALF OF EXTRACTION TRIAL F80-2

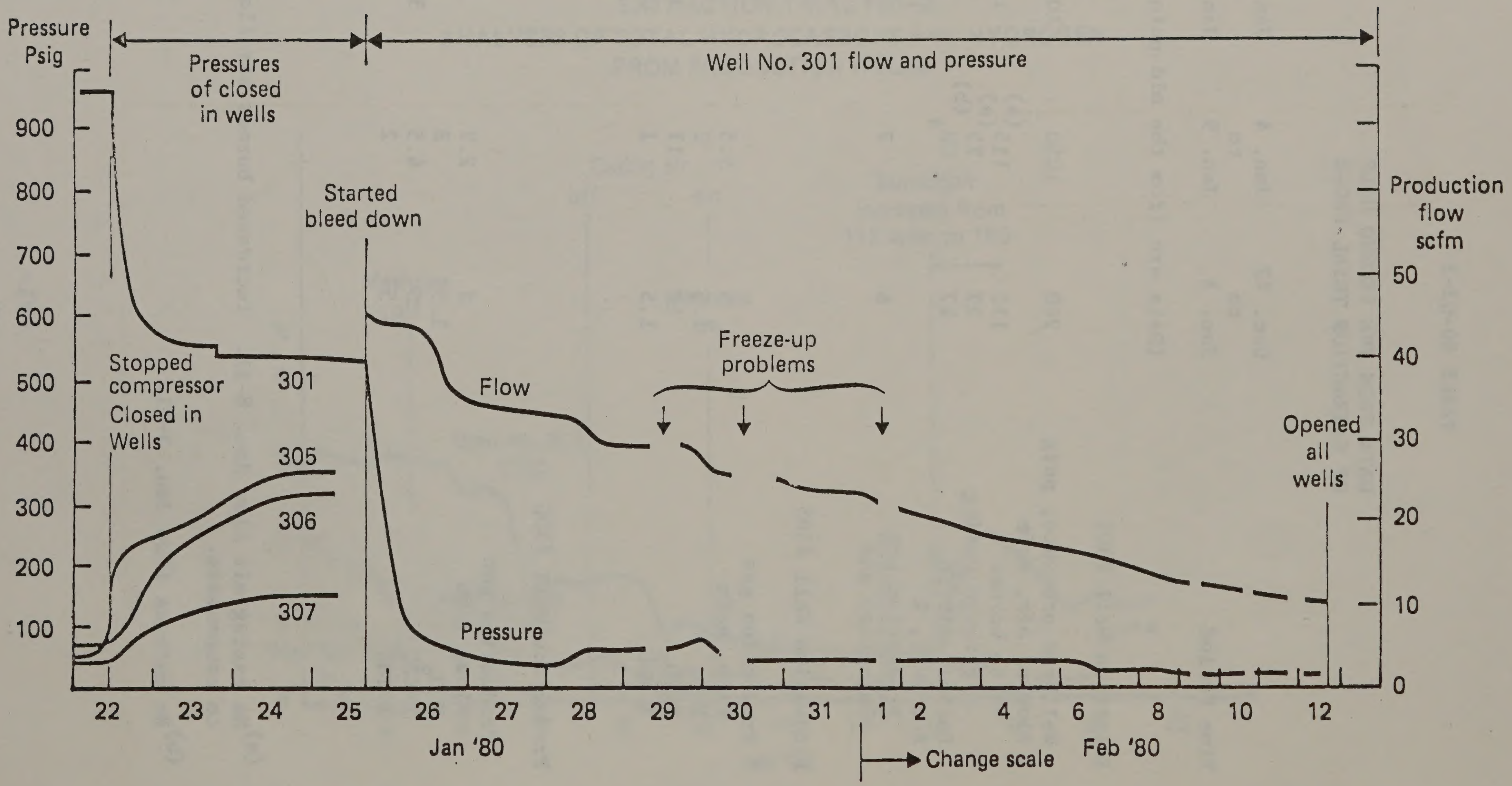
Time Period	Dec. 27 to Jan. 3	Jan. 4 to Jan. 9	Jan. 10 to Jan. 16	Jan. 17 to Jan. 22
	(Data are from the mid-point of each period)			
Injection Well #301				
Wellhead pressure, psig	960	1050	1050	950
Flow of air, scfm				
-- to burner	115	115(a)	125(a)	160
-- through casing	22	25(a)	10	10
Ratio: Air/CH$_4$	27	no CH$_4$(b)	27(b)	20
Recovery, %				
$\frac{\text{Production gas}}{\text{Injection gas}}$	6	7	27	12
Production Well #305				
Production gas				
Flow, scfm	5	5.5	15	9
% O$_2$	1.5	2	15	14
% CO$_2$	12	11	3.5	3.5
% THC	1.5	1	0.8	0.7
Production Well #306				
Production gas				
Flow, scfm	2	2.2	11	3.5
% O$_2$	1.5	8	14	13
% CO$_2$	5	4.5	3.5	3
% THC	3.5	2	1	1.8

(a) No casing air flow Jan. 8-11. Increased burner air flow by 20 scfm to compensate.

(b) No methane flow Jan. 3-11.

FIGURE 80-Q2-5

EXTRACTION TRIAL F80–2
PRESSURES AND FLOWS BEFORE AND DURING BLEED DOWN



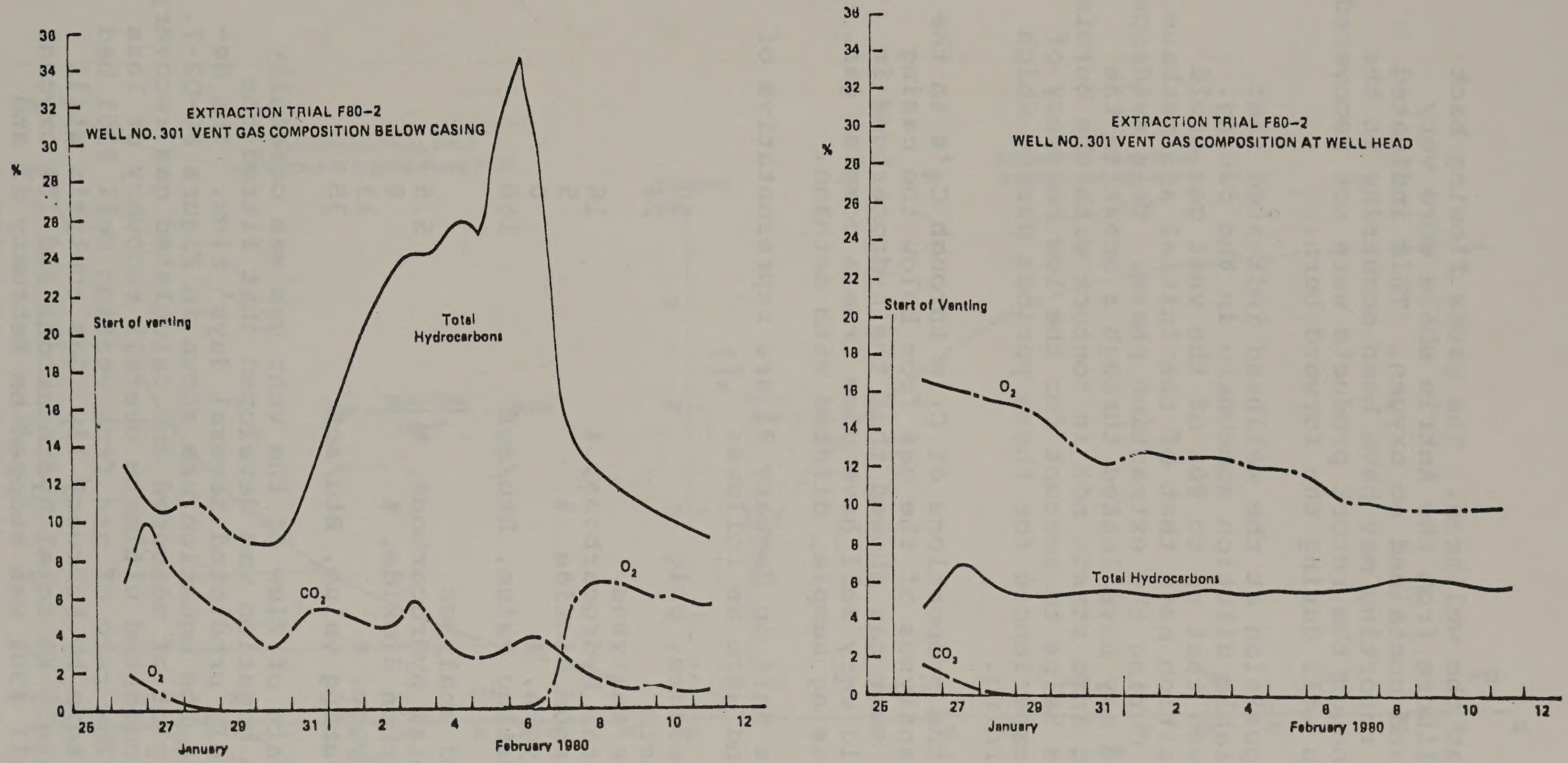


FIGURE 80-Q2-6

WELL #301 VENT GAS COMPOSITION BELOW THE CASING AND AT THE WELLHEAD gas composition at the wellhead. The gases flowing back into the open wellbore from the Antrim shale were very high in methane and contained no oxygen. This indicated that significant retorting may have been occurring in the formation even though the retort products were not recovered at the production well during the forward burn.

The vent gas composition at the wellhead indicated that there was appreciable dilution somewhere in the casing. Calculations showed that up to 90% of the vent gas could have had a composition near that of the initial air/methane mixture injected during the extraction phase. This evidence that injected gas may have leaked through a break in the casing and flowed into strata not in contact with the burning methane and shale helps to account for the low recovery of energy and flow experienced for those periods during which the shale was burning.

A comparison of the proportions of C_1's through C_4's in the chromatographic analyses of the gas from below the casing and the wellhead vent gas showed that the hydrocarbons in the wellhead could very well have come from a complex gas, like the below-casing sample, diluted with methane.

The Well #301 gas data on January 31 are representative of the bleed down and were as follows:

Well pressure, psig	50
Flow, scfm	24
Downhole analyses	
Total hydrocarbons, %	16
Carbon dioxide, %	5
Oxygen, %	0
Heating value, Btu/scf	150
Wellhead analyses	
Total hydrocarbons, %	5.5
Carbon dioxide, %	0
Oxygen, %	13
Heating value, Btu/scf	35

The decreasing rate of flow of the vent gas was carefully monitored and an equation was developed that fitted the data and accurately predicted several days' flow. The decreasing flow and the equation are shown in Figure 80-Q2-7. Also shown is a plot of measured and calculated gas recovery. The projection indicated ultimate overall recovery of less than 32%. The flow rate of gas from venting Well #301 had decreased to 11 scfm by February 11. Gas analysis still showed approximately 6% total hydrocarbons and 10% oxygen. Gas flow from Well #301 was stopped on February 11 and preparations were begun for extraction trial F80-3.

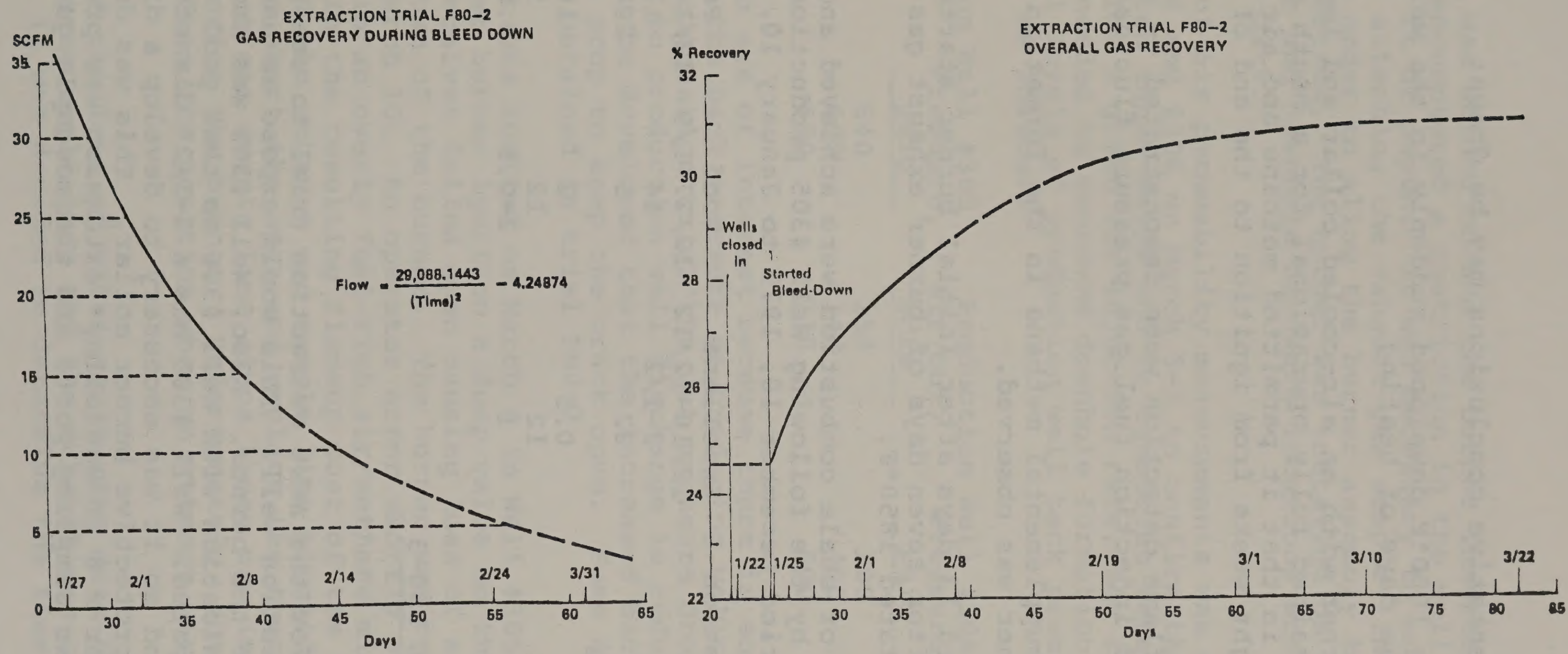


FIGURE 80-Q2-7

GAS RECOVERY DURING FINAL BLEED DOWN, AN EQUATION FITTED TO THE DATA AND PROJECTION OF RECOVERY (DASHED)

Conclusions

The following tentative conclusions may be drawn:

A fire exceeding 1000°F developed suddenly in the well cavity after five days of heating.

The modified burner with an air-cooled collar and improved sample ports remained fully operational for a month and possibly longer in that it permitted methane and air injection for the eight weeks from ignition to the end of the run.

Two methods of flame detection were demonstrated -- exhaust gas sampling and injection fuel gas pressure fluctuation monitoring.

The burning of supplemental methane in the formation rather than at the burner was observed.

The shale ignited 13 days after initial burner startup. This occurred after seven days of burner exhaust gas injection at a calculated 1850°F.

Various degrees of shale combustion were achieved and maintained as shown by the following Well #305 production gas data for the period December 10, 1979 to January 10, 1980:

Degree of combustion	Excellent	Good	Poor
Inclusive dates	12/10-12/12	12/27-1/9	12/14-12/26
Number of days	2-1/2	14	13
Gas flow, scfm	22	5	20→5
Typical analyses			
% O_2	0.5	2	10
% CO_2	12	12	5
% THC	1	2→0.5	0.5

EXTRACTION TRIAL F80-3

Preparations

It was decided for the next extraction trial to use Well #305 as the injection well. This would expose an unretorted shale surface to the burner. Also, Well #305 was known to have good communication with Well #306 so that good flow could be anticipated. Well #305 has a 5-1/2" diameter long-string casing and so it was necessary to develop a different design for the protective burner collar. This was done and a 4-1/2" diameter x 8 ft Hastelloy* extension was prepared with improved gas sampling ports and thermocouple guides.

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*Trademark of the Stellite Division, Cabot Corporation.

When this was welded on and the burner inserted in Well #305, it encountered a restriction in the well casing at about 500 ft of depth. It was necessary to modify the method of attaching the exhaust gas sample line to the burner in order to allow the burner assembly to move by the restriction. The burner was installed on March 4. The burner and downhole hardware locations are shown in Figure 80-Q2-8.

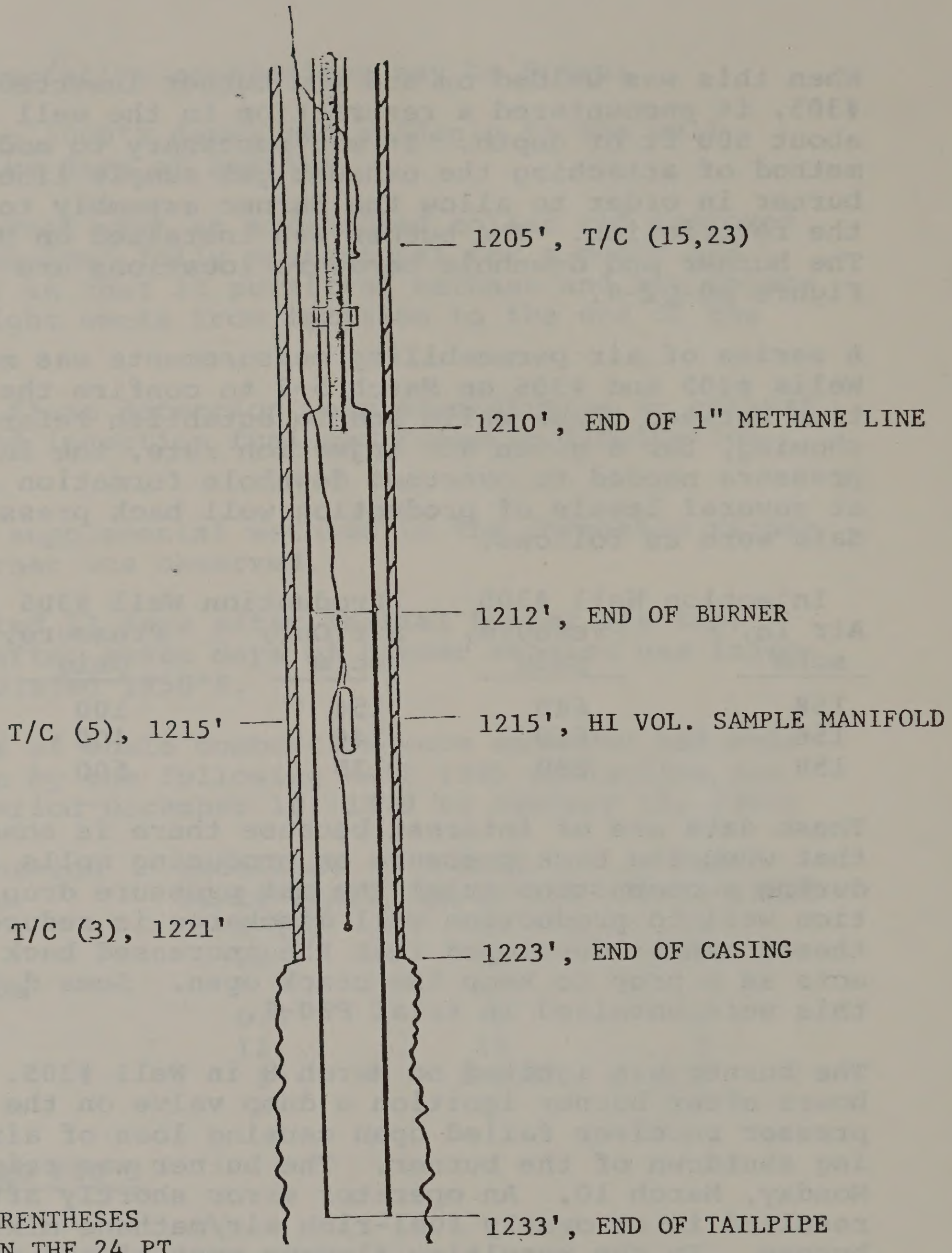
A series of air permeability measurements was made on Wells #305 and #306 on March 5-7 to confirm the communication between these wells and to establish reference data showing, for a given air injection rate, the injection pressure needed to overcome downhole formation resistance at several levels of production well back pressure. The data were as follows:

Injection Well #305		Production Well #306		Air
Air In, scfm	Pressure, psig	Air Out, scfm	Pressure, psig	Recovery, %
158	640	154	100	97.5
156	660	146	400	93.6
158	680	135	600	85.4

These data are of interest because there is some evidence that when the back pressure on producing wells is increased during a combustion trial the net pressure drop from injection well to production well discharge is reduced. A hypothesis can be developed that the increased back pressure acts as a prop to keep the crack open. Some data to support this were obtained in trial F80-3.

The burner was ignited on March 8 in Well #305. Sixteen hours after burner ignition a dump valve on the air compressor receiver failed open causing loss of air and forcing shutdown of the burner. The burner was reignited on Monday, March 10. An operator error shortly after ignition resulted in an overly fuel-rich air/methane mixture at the burner. In the resulting flameup most of the thermocouples failed and the exhaust gas sample line plugged. It was decided to abort the burn and replace the thermocouples and the exhaust gas sample line since these are important tools for monitoring the burner. Unfortunately, the burner would not move from its position when an attempt was made to pull it.

Because of the loss of vital monitoring data brought about by the thermocouple loss and the exhaust gas sample port plugging, it was decided to determine the time delay for



T/C NUMBERS IN PARENTHESES
REFER TO POINTS ON THE 24 PT
RECORDER

FIGURE 80-Q2-8

MODIFIED BURNER AND DOWNHOLE HARDWARE LOCATIONS
IN INJECTION WELL #305, F80-3

flow between Wells #305 and #306. Knowing the time lag would permit using the production gas data from Well #306 to interpret what was happening in Well #305. The data were taken on the night of March 12.

Air was injected into the Well #305 two-inch diameter burner air line until pressure and flow equilibrium were attained. Then the air was replaced with nitrogen. A significant decrease in the oxygen content in the production gas from Well #306 signalled the arrival of the nitrogen and allowed measuring the time delay from Well #305 to #306. An air flow rate of 60 scfm was maintained on the casing throughout the experiment. The injection rate through the burner line was 100 scfm of air or nitrogen for a total of 160 scfm. The results are given below.

	Well #305	Recovery at Well #306		
Test No.	Injection Pressure, psig	Pressure, psig	Flow, scfm	Time For N_2 to Appear
1	690	108	156	43 min
2	760	400	149	73 min

The burner was reignited in its partially disabled condition on March 13. It was then operated at an air/methane ratio of about 25/1. Gas recovery was about 90%, as it had been on March 8 and 10. The shale was ignited during the first day and in 36 hours the oxygen concentration in the Well #306 production gas was 12% O_2 and the gas recovery had dropped to 80%.

Summary of Operations

Detailed topical reports are being prepared on the F80 extraction trials. The discussion below is a summary prepared before all of the data have been evaluated.

Extraction trial F80-3 was brief; the experiment was essentially complete in ten days. Nevertheless, it was the most precise and definitive of all the extraction trials. It also ranks first in quality of data gathered and in the verification of underground events. There was good agreement between the various data gathering systems.

Figure 80-Q2-9 shows the daily quantities of carbon injected in the methane used as fuel and removed in the form of carbon dioxide, carbon monoxide and total hydrocarbons. The graph verifies that there was combustion in the formation in addition to the burning of the injected methane. This combustion began as soon as the burner was ignited on Julian day #73.

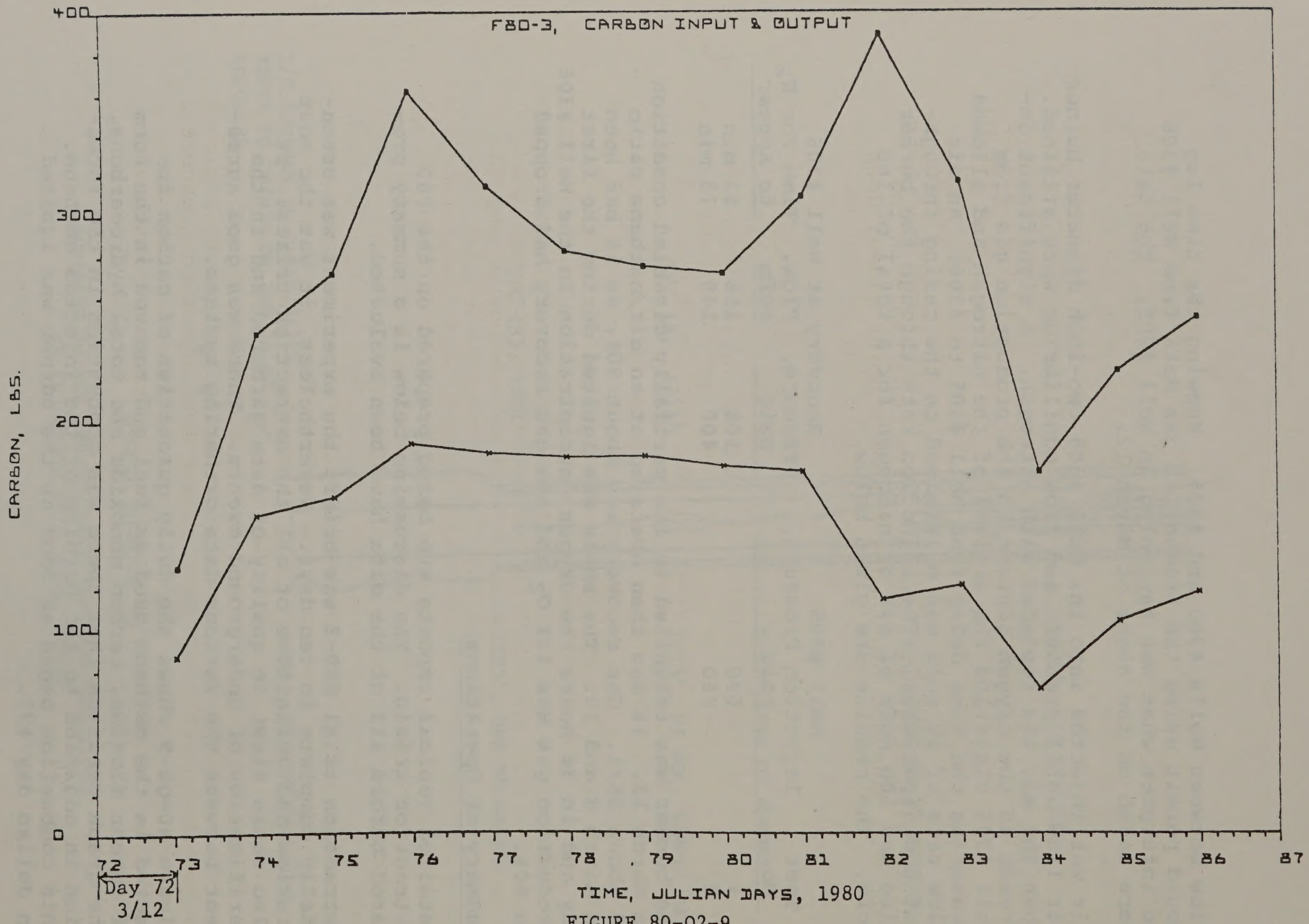


FIGURE 80-Q2-9

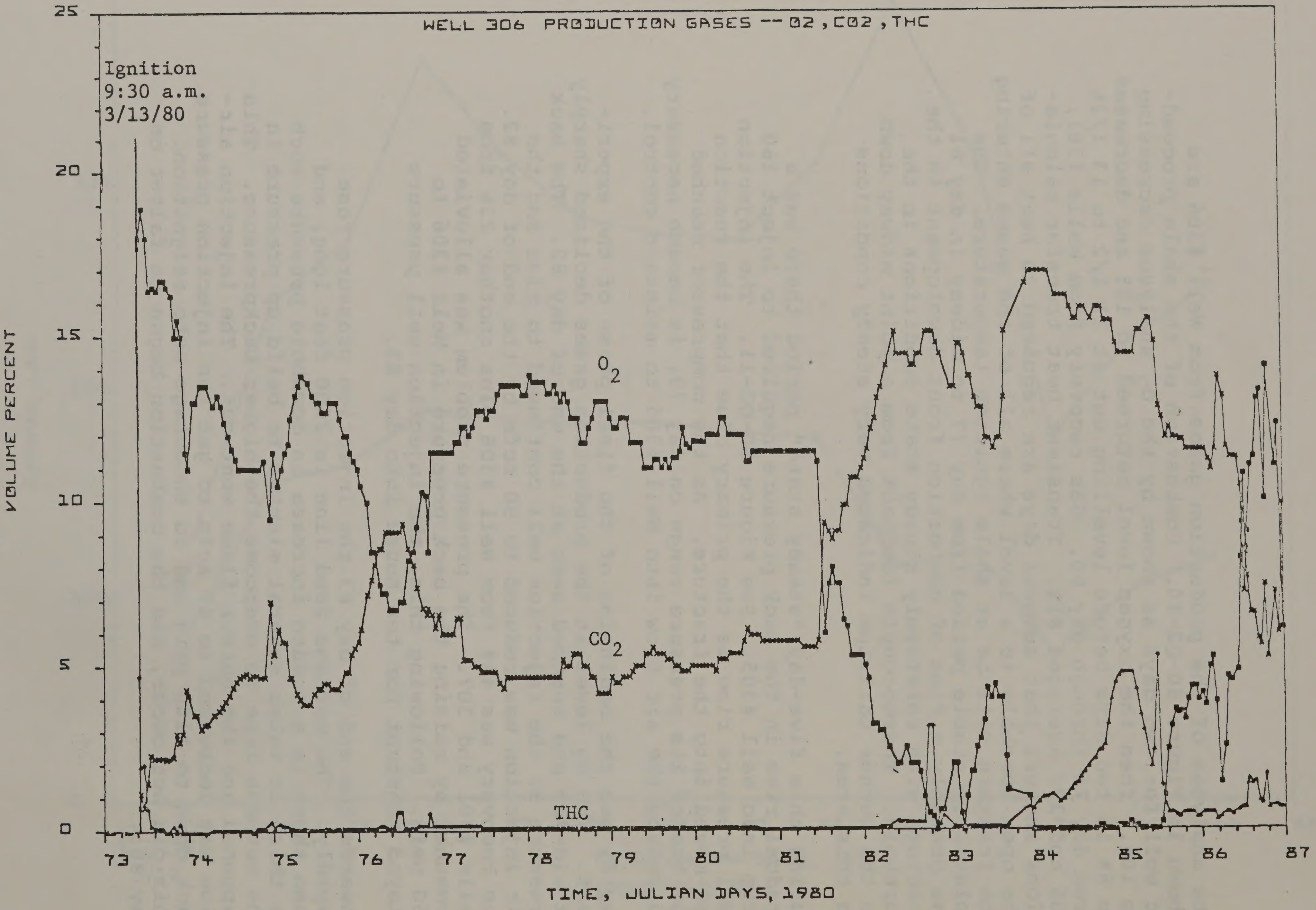
CARBON IN INJECTED METHANE AND IN THE CARBON MONOXIDE, CARBON DIOXIDE AND TOTAL HYDROCARBONS

The analyses of the production gases from Well #306 are shown in Figure 80-Q2-10. Combustion of the shale proceeded well for two days as shown by the O_2 analyses decreasing to 10%. Then the oxygen level returned to 13% and decreased to 8% in two days before levelling out at 11 1/2 to 13 1/2% from day 76 through day 80. Gas recovery from Wells #301, 306 and 307 averaged 81%. Transient heat transfer calculations suggest that several days are required to heat all of the open borehole to a level where all of the gases entering the fracture will be at shale ignition temperature. The relatively stable period from day 77 to midway in day 81 was probably a time of combustion front development in the fracture with relatively steady state conditions in the borehole. Thermocouple feedback from a point midway down on the burner tailpipe indicated very steady conditions in this area.

During this five-day "steady state" period there was a gradual rise in the back pressure required to inject 160 scfm into Well #305. See Figure 80-Q2-11. The injection well pressure rise is the primary clue that the reaction had moved into the fracture. As the compressor reached the top of its pressure range on day 79, it became necessary to reduce the air flow into Well #305 to maintain control.

Day 81 was the beginning of the final phase of the experiment. The O_2 level in the production gases declined sharply at mid-day and reached zero at the end of day 82. The back pressure at the injection well continued to rise and the air injection was reduced to 90 scfm by the end of day 82. Gas recovery was 44% from Well #306 plus another 23% from Wells #301 and 307. The pressure problem was alleviated somewhat by raising the back pressure in Well #306 to 750 psig. Following this, the injection well pressure stayed constant for ten hours into day 83.

Towards the end of day 83 the injection pressure rose rapidly. The methane feed line is 2500 feet long, and when there is a sudden increase in downhole pressure such as this, it takes several minutes to build up pressure in the methane line to overcome the higher backpressure. This happened and the burner flame went out. The injection airflow was decreased to 40 scfm to get the injection pressure back down to 1100 psig and to encourage auto reignition. This did not occur, and the combustion began to falter on day 85.


WELL 306 PRODUCTION GASES -- O2, CO2, THC

Ignition
9:30 a.m.
3/13/80

FIGURE 80-Q2-10

WELL #306 PRODUCTION GAS ANALYSES, FIRST TWO WEEKS OF EXTRACTION TRIAL F80-3

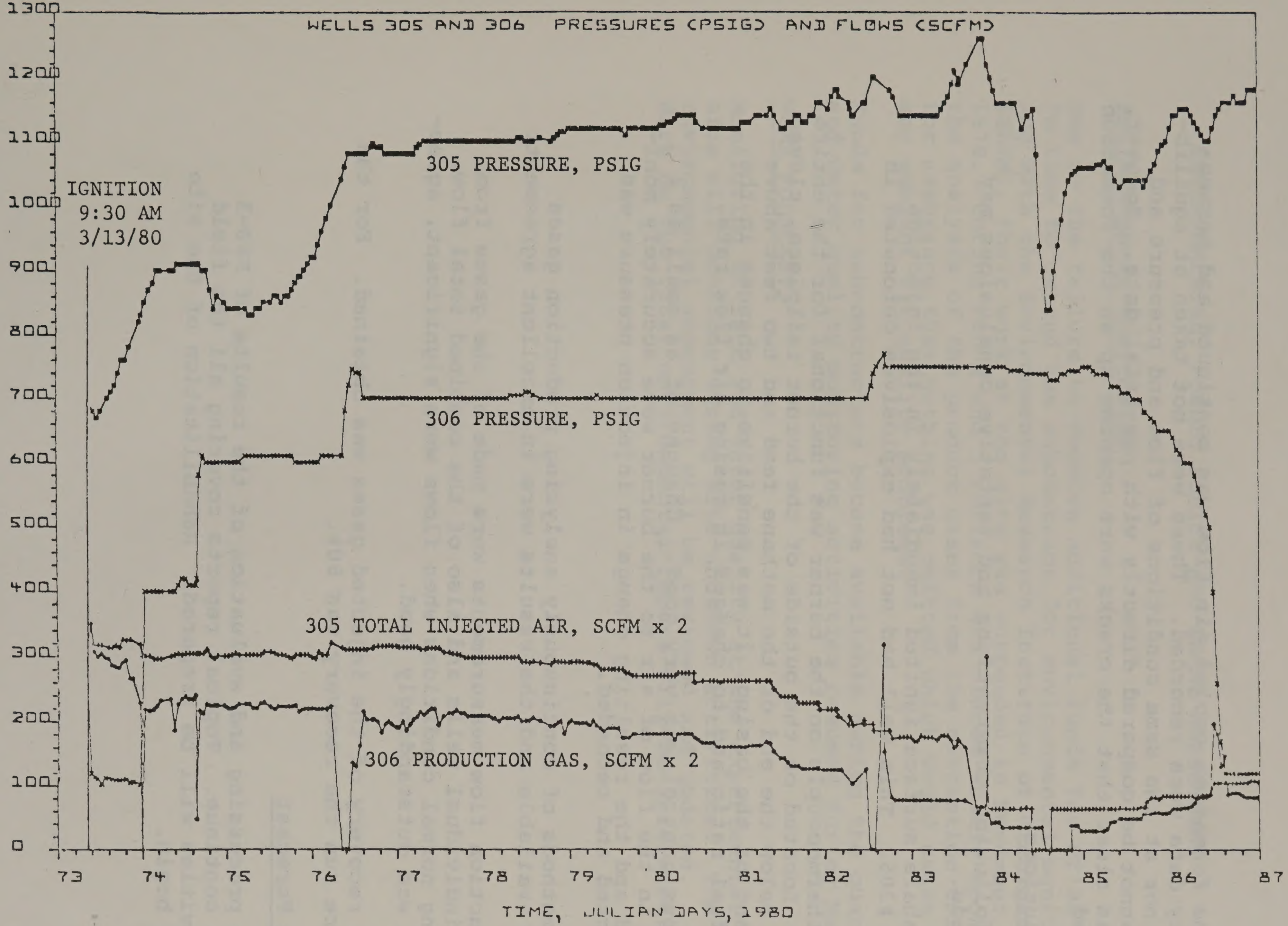


FIGURE 80-Q2-11

PRESSURES AND FLOWS FOR INJECTION WELL #305 AND PRODUCTION WELL #306
FOR THE FIRST TWO WEEKS OF EXTRACTION TRIAL F80-3

As the formation cooled air flow was continued and permeability data were recorded. These were not taken at equilibrium nor at the same conditions of flow and pressure and so cannot be compared directly with pre-trial data. However, it was clear that the cracks were opening up as the formation cooled.

Conclusions

The following observations and tentative conclusions may be made.

The shale surface ignited immediately in the injection Well #305. This well had not had explosives detonated in it.

One thermocouple on the burner was functional for the entire run. Located on the outside of the burner tailpiece, eleven feet below the end of the methane feed and two feet above the end of the casing, it was sensitive to changes in the air/fuel ratio and to changes in casing air flow rate.

Process control was very good. Changes of as small as 2 scfm in the flow of air to the burner were accurately monitored and the resulting change in injection pressure was detected and recorded.

Two methods of continuously analyzing production gases were available and the results were in excellent agreement.

Production flow measurements were made of the gases from the individual wells and also of the combined total flow. During normal conditions when flows were significant, agreement was outstandingly good.

Good recovery of the injected gases was obtained. For the entire run the recovery was 80%.

Work Forecast

Data processing and evaluation of the results of F80-3 will continue. Topical reports covering all the field activities will be prepared. Rehabilitation of the site will begin.

ENVIRONMENTAL, PUBLIC POLICY AND LEGAL ASSESSMENT

ENVIRONMENTAL MONITORING

Due to the failure to receive additional funds for FY'80 in time to extend the subcontract for environmental monitoring with the Environmental Research Institute of Michigan (ERIM), their work at the site was suspended in November 1979. During F80-2 and 3 reliance was placed solely upon the analysis of the product gases from the extraction trials for assurance that nothing was emitted which would cause any ambient air quality problems.

Funds for subcontractors became available during the quarter and water quality monitoring activities resumed during March.

WORK FORECAST

Monitoring of land and water quality at the experimental site will continue during site shutdown activities. The environmental assessment will be reviewed and updated. Work on the final environmental report will be initiated.

CONCLUSIONS

SHALE CHARACTERIZATION

Work continues under several subcontracts with Michigan universities on core samples and well cuttings samples from many locations in the Michigan Basin.

IN SITU FRACTURING AND ASSESSMENT

All work on this task has been completed except for the plugging of the wells and the preparation of reports. Work on the reports is underway.

IN SITU EXTRACTION TRIALS

Extraction trials F80-2 and F80-3 were completed. Data processing and evaluation are in process. In both runs, shale was ignited in situ, modest quantities of low BTU gas were produced, and recovery rates decreased during periods when the formation was being heated by combustion of the injected methane or by burning shale.

ENVIRONMENTAL, PUBLIC POLICY AND LEGAL ASSESSMENT

Analyses of production well gases during combustion trials gave no indication that any air pollutants were being produced. Water quality monitoring activity was resumed in March, but no analytical data have been reported. No new land or water quality impacts were observed.

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CONCLUSIONS

SHALE CHARACTERIZATION

Work continued under [illegible] characterization with [illegible] interpretation of core samples and well cuttings samples from many locations in the Michigan Basin.

IN SITU FRACTURING AND [illegible]

All work on this task has been completed except for the plugging of the wells and the preparation of reports. Work on the reports is underway.

IN SITU EXTRACTION TRIALS

Extraction trials [illegible] were completed. Some processing and [illegible] is in progress. [illegible] shale was ignited [illegible] modest quantities of low Btu gas were produced, [illegible] periods when the [illegible] was being heated by [illegible] of the injected [illegible] by the shale.

ENVIRONMENTAL [illegible] AND [illegible]

Analyses of [illegible] gave no indication that [illegible] were [illegible]. [illegible]